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# The effect of walking speed on quality of gait in older adults

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ABSTRACT

*Background:* Gait quality characteristics can contribute to the identification of individuals at risk of falls. Since older adults with high fall risk tend to walk slower than older adults with a lower fall risk, walking speed may underlie differences in gait quality characteristics.
*Research question:* How does walking speed affect gait quality characteristics in older people?
*Methods:* We investigated the effect of walking speed on gait characteristics in 11 older adults (aged 69.6 ± 4.1 years). Trunk accelerations (Dynaport MoveMonitor) were recorded during 5 min of treadmill walking at four different speeds. From these trunk accelerations we calculated step frequency, root mean square, harmonic ratio, index of harmonicity, sample entropy and logarithmic divergence rate per stride.
*Results:* Our results showed that all gait characteristics were affected by walking speed, except for sample entropy in antero-posterior (AP) direction. An increase in walking speed resulted in a higher step frequency, higher standard deviation, more symmetric gait, more smooth vertical (VT) accelerations, less smooth accelerations in medio-lateral (ML) and AP directions, less regular dynamics in ML direction, more regular dynamics in VT direction, and a more stable gait pattern overall.
*Significance:* These findings suggest that, within a range of 0.5–1.4 m/s, a lower walking speed results in a lower gait quality, which may underlie differences in gait quality between older fallers and non-fallers.

## 1. Introduction

Every year, one-third of people over 65 years of age falls at least once [1]. Observational studies indicate that a large proportion of falls among older adults occurs during walking [2,3]. Previous studies have shown that gait characteristics can differentiate fallers from non-fallers [4–6]. Moreover, such gait characteristics are predictive of future falls [7–9]; older people at high risk for falls tend to walk with a lower stride frequency, lower gait intensity, lower harmonic ratio, higher index of harmonicity, lower sample entropy and lower dynamic stability. The concurrent findings of a lower habitual walking speed in individuals at high risk of falls leads to the question whether walking speed could be a mediator in the relation with fall risk. Therefore, an understanding of the effect of walking speed on these gait characteristics is needed to interpret the comparison of gait characteristics between individuals or groups who tend to walk at different speeds.

Previous studies on the effect of walking speed on gait characteristics provide conflicting results [10–15]. Such studies in young participants reported that harmonic ratio, a measure of gait symmetry, generally increases between slow to preferred walking speed, but may continue this increase or level off or even decline between preferred and high walking speed [11,12,15]. In a study with older participants, Lowry and colleagues showed that harmonic ratios were gradually lower at self-selected very slow and slow walking speed compared to preferred, fast and very fast speed [10]. However, the effect of absolute walking speed remains unclear. For gait stability, as indicated by the logarithmic divergence rate of gait kinematics thought to reflect responses to small perturbations, inconsistent findings on the effect of walking speed have been reported [13,14,16–19]. Such inconsistent findings can be attributed to methodological choices [13], which suggest that the effect of walking speed on dynamic stability needs to be evaluated for the method that is employed. Moreover, no previous studies systematically investigated the effect of walking speed on index of harmonicity and sample entropy, although these gait characteristics are also extensively used to evaluate gait dynamics. Hence, the purpose of this study was to systematically assess the effect of walking speed in older adults on a comprehensive set of gait quality characteristics that has previously been associated with fall risk, i.e., on stride frequency, gait intensity, gait symmetry, gait smoothness, gait regularity and gait stability. We hypothesized that over a speed range from 0.5 up to

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**Table 1**
Descriptive characteristics.

| | N or mean (sd) |
|---|---|
| Gender | 6 ♀ / 5 ♂ |
| Age (years) | 69.6 (4.1) |
| Weight (kg) | 73.1 (9.2) |
| Height (m) | 1.74 (0.05) |
| BMI (kg/m$^2$) | 24.3 (3.6) |
| Leg length (m) | 0.93 (0.03) |
| Preferred walking speed (m/s) | 1.11 (0.10) |
| Fallers (≥ 1 fall in the past year) | 3 |

1.4 m/s, faster gait would be less variable and more regular, stable, and symmetric.

## 2. Methods

### 2.1. Participants

After obtaining approval for the protocol from the local ethical committee of the Department of Human Movement Sciences (protocol ECB 2015-10), 11 healthy older adults were recruited (Table 1). Participants were selected based on the following inclusion criteria: 1) over 65 years of age; 2) BMI below 30 kg/m$^2$; 3) no need for a walking aid for daily ambulation; 4) no known problems with performance of daily activities; 5) no known problems with visual, auditory or vestibular systems; and 6) not diagnosed with Parkinson's disease, osteoarthritis, history of stroke or cardiac problems. All participants came to our gait laboratory and provided signed informed consent.

### 2.2. Experimental protocol

Participants' body height and body mass were measured with clothes and shoes on. Participants were asked to stand on a treadmill (R-mill, ForceLink, The Netherlands), where a tri-axial accelerometer (Dynaport Hybrid, McRoberts, The Netherlands, sample frequency: 100 Hz, range: ± 6 g, resolution: ± 3 mg) was fixed to their lower trunk at the level of L5 with an elastic belt. In the anatomical position, the direction of the vertical (VT), medio-lateral (ML) and antero-posterior (AP) axis of the tri-axial accelerometers was from caudal to cranial, from left to right and from dorsal to ventral, respectively. After placement of the accelerometer, the participants were fitted with a safety harness around their upper trunk. It was made sure that the safety harness did not interfere with the accelerometer and participants were instructed not to grasp the safety harness or the safety bars of the treadmill for balance during the trials.

Our sample included participants with and without experience with treadmill walking. Therefore, before starting the experiment, the participants walked at a comfortable walking speed on the treadmill until they reported to be acclimated to treadmill walking. Each participant's preferred walking speed (PWS) was subsequently established using a protocol described by Jordan et al. [20]. Starting from 1.8 km/h, the treadmill's speed was increased by steps of 0.1 km/h until the participant indicated that the current speed was their preferred walking speed. Subsequently, the treadmill speed was increased by 1.5 km/h, after which its speed was decreased by steps of 0.1 km/h until the participant indicated that the current speed was their preferred walking speed. This procedure was repeated until both preferred speeds were within 0.4 km/h of each other, and their average was selected as preferred treadmill walking speed. The average PWS of our participants was 4.0 (SD 0.4) km/h (which equals 1.1 SD 0.1 m/s), with a between-subject range of 3.5 to 4.5 km/h. After we determined PWS, trunk accelerations were obtained during walking at 1.8, 2.9, 4.0 and 5.0 km/h (i.e. 0.5, 0.8, 1.1, and 1.4 m/s). The order of the four fixed walking speed trials was randomized. Note that none of the participants had a PWS that exceeded our maximum fixed walking speed of 5.0 km/h. Measurements were started when the treadmill and participant were at a constant speed and each trial lasted for five minutes to ensure collection of sufficient strides [21]. Participants were allowed to rest between trials and the next trial was started only after the participant indicated to be fully rested.

### 2.3. Data processing

MATLAB (vR2011b, Mathworks, USA) was used to analyze the trunk acceleration data. First, the acceleration data were converted from g to m/s$^2$. Subsequently, the raw accelerations were realigned with the anatomical axes using the sensor's orientation with respect to gravity [22] and an optimization of the left-right symmetry [23]. The resulting data were used to calculate the following gait characteristics: 1) stride frequency [6]; 2) root mean square (RMS) of the accelerations as a measure of gait intensity; 3) harmonic ratio as a measure of gait symmetry [15]; 4) index of harmonicity as a measure of gait smoothness [24]; 5) mean logarithmic rate of divergence per stride based on a 10-sample delayed embedding in seven dimensions as a measure of gait stability [25]; and 6) sample entropy with embedding dimension 5 and tolerance 0.3 as a measure of gait regularity [26]. These gait characteristics were determined for the VT, ML and AP direction where appropriate. More details on these algorithms and the rationale for specific input values can be found elsewhere [6,7].

### 2.4. Statistical analyses

The effect of walking speed on the gait quality characteristics was examined using a one-way repeated measures analysis of variance (ANOVA) or a non-parametric Friedman test. Normality was checked by visual inspection of the data and a Shapiro-Wilks test. The assumption of normality was violated for the harmonic ratio in ML direction, the index of harmonicity in AP and ML directions and sample entropy in AP directions. For normal-distributed characteristics, we reported the Greenhouse-Geisser correction in case of violation of the assumption of sphericity and a Greenhouse-Geisser epsilon of < 0.75; we reported the Huynh-Feldt correction in case of violation of the assumption of sphericity and a Greenhouse-Geisser epsilon of ≥0.75. When a significant main effect was found, post-hoc paired t-tests or Wilcoxon signed ranks test with a Bonferroni correction were used to identify where the specific differences occurred between the four speeds. The post-hoc t-tests were also used to calculate the 95% CI of each difference and to determine the effect size (partial eta$^2$). Effect sizes were unavailable for the Wilcoxon signed rank tests. An additional sensitivity analyses of the effect of speed relative to preferred walking speed on the gait characteristics was performed and presented as an Appendix. All statistical analyses were performed using SPSS Statistics (version 22.0, IBM, USA) and a *p*-value of 0.05 or lower was considered significant.

## 3. Results

On average, preferred walking speed was 1.1 (SD 0.10) m/s and did not exceed the fixed maximum walking speed of 1.4 m/s for any of our participants.

Walking speed had a significant effect on all gait quality characteristics (all $p < 0.05$, $\eta_p^2 \geq 0.24$,) except sample entropy in AP direction (Fig. 1 and Table 2).

Stride frequency and RMS in VT, ML and AP directions showed a positive main effect ($p < 0.001$, $\eta_p^2 \geq 0.68$), reflecting a higher step frequency and gait intensity with increasing walking speed. The post-hoc tests revealed that stride frequency and RMS significantly differed between all walking speeds in all directions (all $p < 0.05$).

There was a positive main effect of speed on harmonic ratio in all directions (VT and AP $p < 0.001$ $\eta_p^2 \geq 0.77$, ML $p < 0.05$ $\eta_p^2$ = N/A), reflecting a more symmetric gait with increasing walking speed. The

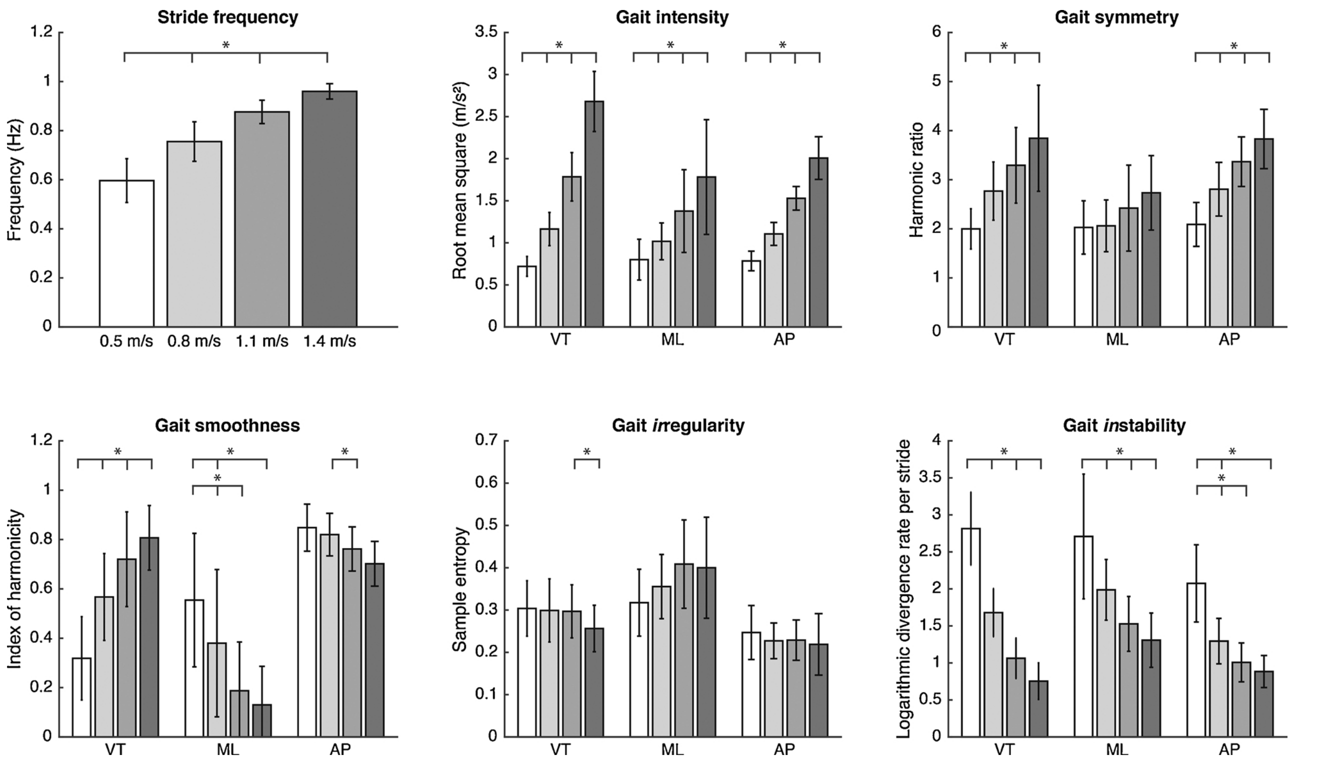


**Fig. 1.** The effect of walking speed on gait characteristics. The white bars indicates values at a walking speed of 0.5 m/s, light grey bars at 0.8 m/s, grey bars at 1.1 m/s, and dark grey bars at 1.4 m/s. * denotes a significant difference at $p < 0.05$).

harmonic ratio was significantly different between all walking speeds for the AP and VT directions. Although we found a significant main effect for the ML direction, the post-hoc Wilcoxon signed-rank tests with Bonferroni correction revealed no significant differences between walking speeds.

The index of harmonicity showed direction dependent effects of speed; with increasing walking speed, the index of harmonicity increased in VT direction ($p < 0.001$, $\eta_p^2 = 0.77$), while it decreased in ML and AP directions ($p < 0.001$, $\eta_p^2$ = N/A). This indicated smoother accelerations in VT direction and a less smooth acceleration in ML and AP directions. Post-hoc tests revealed that the index of harmonicity in ML direction at 0.8 m/s was significantly lower than at 0.5 m/s ($p < 0.05$) and that the index of harmonicity at 1.4m/s and 1.1m/s was significantly lower than at 0.8m/s ($p < 0.05$). However, no significant difference was found between the walking speeds of 1.1 m/s and 1.4 m/s ($p > 0.05$). Furthermore, the index of harmonicity in AP direction at 0.5 m/s and 0.8 m/s were significantly higher than at 1.1 m/s and 1.4 m/s ($p < 0.05$). We found no significant difference between 0.5 m/s and 0.8 m/s and between 1.1 m/s and 1.4 m/s.

There was no effect of speed on sample entropy in the AP direction. For the VT direction, a negative main effect of speed was found ($p < 0.05$, $\eta_p^2 = 0.24$), indicating increased regularity at higher walking speeds, whereas for the ML direction, a positive main effect was found ($p < 0.05$, $\eta_p^2 = 0.33$), indicating less regularity at higher walking speeds. However, the main effects in both directions were weak as illustrated by the relatively small effect sizes. Furthermore, the post hoc tests for the sample entropy in VT direction revealed only a significant difference between walking speeds of 1.1 m/s and 1.4 m/s ($p < 0.05$). For the ML direction, the post-hoc tests revealed no significant differences between speeds ($p > 0.05$).

The logarithmic divergence rate per stride showed a negative main effect of speed for all directions ($p < 0.001$, $\eta_p^2 \geq 0.70$), reflecting more stable gait dynamics at higher walking speeds. Logarithmic divergence rate per stride in VT and ML directions differed significantly between all speeds ($p < 0.05$). The logarithmic divergence rate per stride in AP direction was significantly different between all walking speeds ($p < 0.05$), except between 1.1 m/s and 1.4 m/s ($p > 0.05$).

## 4. Discussion

We examined, in older adults, the effects of walking speed on gait characteristics that previously have been associated with increased fall risk. Our systematic comparisons show that all gait characteristics, except sample entropy in AP direction, were significantly affected by walking speed. Furthermore, our results indicate that with increasing walking speed, stride frequency, gait intensity, symmetry and stability increase, reflecting qualitatively better gait. For gait smoothness and gait regularity, we observed direction dependent effects. With increasing walking speed, smoothness in VT direction increased suggesting qualitatively better gait, while smoothness in ML and AP directions decreased. Sample entropy in ML and VT directions was weakly affected by speed, as indicated by significant main effects with small effect sizes and few significant effects in the post-hoc comparisons.

Our findings of increasing stride frequency and gait intensity, i.e. the RMS of trunk accelerations, with higher walking velocities agree with the literature [11,12]. A higher walking speed generally leads to larger amplitudes of accelerations and consequently gait intensity was closely related to walking speed ($\eta_p^2$ VT = 0.96, $\eta_p^2$ ML = 0.68, $\eta_p^2$ AP = 0.96). This suggests that gait intensity may provide limited additional information about gait quality if walking speed is known. Our findings further indicate a positive effect of walking speed on harmonic ratios, suggesting a more symmetrical gait pattern at higher speeds. Similar results have been observed in comparable studies [10–12,15]. Latt and colleagues and Menz and colleagues [11,12] showed an optimum in gait symmetry at preferred walking speed during over ground walking in young adults, however our data do not suggest such a curvilinear relation (Fig. 1). This could be related to our selection of fixed walking speeds for all participants, instead of percentages of their preferred walking speed. However, we could not discern any optimum

**Table 2**
Statistical tests for the effect of walking speed on gait characteristics.

| | Walking speed | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Main effect<br>*F (df1, df2)*<br>*or $X^2$ [df]* | *p*-value | Effect size<br>$\eta_p^2$ | Means<br>*Mean (SD) or Median [IQR]* | | | | Posthoc comparisons<br>*95% CI diff or Z* | | |
| | | | | 0.5 m/s | 0.8 m/s | 1.1 m/s | 1.4 m/s | 0.5-0.8 m/s | 0.8-1.1 m/s | 1.1-1.4 m/s |
| **Stride frequency** | 192.2 (1.6, 16.2) | < 0.001 | 0.95 | 0.60 (0.09) | 0.76 (0.08) | 0.88 (0.05) | 0.96 (0.03) | 0.12 - 0.20* | 0.08 - 0.16* | 0.05 - 0.11* |
| **Standard deviation VT** | 256.7 (1.7, 17.1) | < 0.001 | 0.96 | 0.72 (0.12) | 1.16 (0.20) | 1.79 (0.29) | 2.68 (0.36) | 0.29 - 0.60* | 0.49 - 0.76* | 0.66 - 1.12* |
| **Standard deviation ML** | 21.0 (1.1, 11.4) | < 0.001 | 0.68 | 0.80 (0.24) | 1.02 (0.22) | 1.38(0.49) | 1.78 (0.68) | 0.02 - 0.41* | 0.03 - 0.69* | 0.16 - 0.65* |
| **Standard deviation AP** | 271.1 (1.4, 13.6) | < 0.001 | 0.96 | 0.78 (0.12) | 1.11 (0.14) | 1.53 (0.14) | 2.01 (0.25) | 0.26 - 0.38* | 0.33 - 0.52* | 0.34 - 0.62* |
| **Harmonic ratio VT** | 33.5 (1.4, 14.3) | < 0.001 | 0.77 | 2.00 (0.41) | 2.77 (0.59) | 3.30 (0.77) | 3.85 (1.08) | 0.48 - 1.06* | 0.01 - 1.05* | 0.06 - 1.04* |
| **Harmonic ratio ML+** | 7.7 [3.0] | < 0.05 | N/A | 2.13 [0.48] | 2.10 [0.79] | 2.20 [0.50] | 2.51 [0.78] | −0.27 | −1.42 | −2.05 |
| **Harmonic ratio AP** | 56.9 (3.0, 30.0) | < 0.001 | 0.85 | 2.01 (0.45) | 2.81 (0.55) | 3.36 (0.50) | 3.83 (0.60) | 0.40 -1.04* | 0.17 - 0.95* | 0.09 - 0.84* |
| **Index of harmonicity VT** | 32.6 (1.4, 13.7) | < 0.001 | 0.77 | 0.32 (0.17) | 0.57 (0.18) | 0.72 (0.19) | 0.81 (0.13) | 0.05 - 0.45* | 0.05 - 0.26* | 0.02 - 0.16* |
| **Index of harmonicity ML+** | 26.5 [3.0] | < 0.001 | N/A | 0.50 [0.56] | 0.32 [0.61] | 0.09 [0.36] | 0.06 [0.22] | −2.85* | −2.85* | −1.78 |
| **Index of harmonicity AP+** | 18.6 [3.0] | < 0.001 | N/A | 0.87 [0.09] | 0.85 [0.16] | 0.77 [0.16] | 0.71 [0.16] | −1.42 | −2.76* | −1.96 |
| **Sample entropy VT** | 3.2 (3.0, 30.0) | < 0.05 | 0.24 | 0.30 (0.07) | 0.30 (0.07) | 0.30 (0.06) | 0.26 (0.05) | −0.06-0.07 | −0.04 - 0.05 | 0.00 - -0.80* |
| **Sample entropy ML** | 5.0 (1.6, 15.9) | < 0.05 | 0.33 | 0.32 (0.08) | 0.36 (0.08) | 0.41 (0.10) | 0.40 (0.12) | −0.03 - 0.11 | −0.03 - 0.13 | −0.05 - 0.03 |
| **Sample entropy AP+** | 6.0 [3.0] | > 0.05 | N/A | 0.22 [0.11] | 0.23 [0.05] | 0.22 [0.05] | 0.20 [0.04] | N/A | N/A | N/A |
| **Logarithmic divergence rate (/stride) VT** | 116.7 (1.4, 13.9) | < 0.001 | 0.92 | 2.82 (0.50) | 1.68 (0.32) | 1.06 (0.27) | 0.75 (0.25) | −1.55 - -0.73* | −0.88 - -0.36* | −0.42 - -0.20* |
| **Logarithmic divergence rate (/stride) ML** | 22.9 (1.1, 11.5) | < 0.001 | 0.70 | 2.71 (0.84) | 1.99 (0.41) | 1.53 (0.37) | 1.31 (0.37) | −1.28 - -0.16* | −0.78 - -0.14* | −0.42 - -0.02* |
| **Logarithmic divergence rate (/stride) AP** | 90.0 (1.4, 14.1) | < 0.001 | 0.90 | 2.08 (0.52) | 1.29 (0.31) | 1.01 (0.26) | 0.88 (0.22) | −1.03 - -0.53* | −0.47- -0.11* | −0.26 - 0.02 |

Notes: + indicates gait characteristics that were not normally distributed and * indicates $p < 0.05$. VT = vertical direction; ML = medio-lateral direction; AP = antero-posterior direction. N/A = not applicable.

around PWS at an individual level (see Appendix Figure A1). Another explanation for these differences might be that treadmill walking induces more consistent and stable gait, as suggested by previous findings of lower stride time variability and lower logarithmic rate of divergence on a treadmill compared to over ground [27]. This might shift the optimum of gait symmetry, even in our older participants, towards or beyond our maximum walking speed of 1.4 m/s. Further, Lowry and colleagues [10] showed that similar trends of walking speed on gait symmetry were observed between young (aged 22.1, SD 0.9) and older adults (aged 66.3, SD 2.6). These trends only started to deviate at very fast speeds (> 1.82 m/s) for harmonic ratio in VT. However, different trends were observed between older adults and old-older adults (aged 82.47, SD 2.2), showing only less symmetric walking patterns at very high age. In an extensive methodological study, Stenum and colleagues [13] reported that the effect of walking speed on the logarithmic divergence rate is sensitive to methodological choices and therefore difficult to compare across studies. We did not find studies exploring the effect of walking speed on the logarithmic divergence rate per stride using comparable settings to the ones we used. However, as recent papers linked this measure with these settings to fall risk, it is key to gain insight into its association with walking speed. Still, almost all previous studies, irrespective of methodological choices, report a significant effect (either positive or negative) of walking speed on logarithmic divergence rate [23,26]. Our results show a significant decrease of the logarithmic divergence rate per stride in all directions, indicating a more stable gait pattern at higher speeds.

Our results further suggest that in older adults, a higher walking speed results in qualitatively better gait in terms of symmetry, stability, and smoothness in VT. Higher gait symmetry, gait stability and gait smoothness in VT have been associated with a decreased risk for falls in community-dwelling older adults [6–8,28]. Our results further indicate that a higher walking speed results in decreased smoothness in ML and AP. Since higher smoothness of gait in ML and AP has been associated with increased risk for falls [8,28], these results suggest that walking faster results in a “safer” gait pattern. These results remained unchanged when we analysed the effect of speed relative to preferred walking speed (which ranged between 45 (SD 4) to 126 (SD 12) percent of preferred walking speed) on gait characteristics (see Appendix). Differences in walking speed between people at high or low risk for falls might thus partially explain differences in gait quality between these groups. Future studies are required to determine whether a lower habitual walking speed among people with a high risk for falls is due to impaired neuromuscular capacities or a compensation to remain stable.

The current study provides novel information by systematically investigating the effect of walking speed on gait quality characteristics but also has its limitations. First, our participants were able to walk at speeds up to 1.4 m/s, which suggests that they were relatively fit. Different associations with walking speed could occur when evaluating individuals who are more frail and unable to walk as fast. However, the average age of our participants was 70 years and 3 out of 11 participants reported that they had fallen in preceding year, suggesting that we had heterogeneity in fall risk. Second, the use of a treadmill may limit generalizability of our results to daily-life since gait on a treadmill tends to be less variable, more symmetric and more stable [29]. However, a treadmill was necessary to precisely control walking speed and make sure that there were no fluctuations during the 5-minute walking period. Furthermore, based on stride frequency, we estimated the average number of strides taken during the 5-minute walking assessments to range between 179 (SD 27) at 0.5 m/s and 288 (SD 10) at 1.4 m/s, which appears limited but sufficient to reliably estimate gait characteristics [21]. Third, underlying gait adaptations resulting in more stable gait dynamics cannot readily be measured with accelerometry. Winter and colleagues [30] showed that older adults generally exhibit a longer double support stance period, a shorter stride length, decreased push-off power and a more flat-footed landing, in comparison to young adults. They suggested that these adaptations help to maintain stable gait dynamics. However, due to the use of accelerometry, we could not verify whether our subjects used such adaptations when treadmill speed was lowered.

In conclusion, most of the analyzed gait measures showed that quality of gait increases with increasing walking speed up to 1.4 m/s. The effect of walking speed on harmonic ratios in all directions, logarithmic divergence rate per stride in all directions, index of harmonicity and sample entropy in VT direction suggest that slowing down is accompanied by a decrease of gait quality in older adults.

## Conflict of interest

BH currently works at McRoberts BV, the company that manufactured the sensors used in the study. This company had no involvement in the study design, study execution, or writing of this manuscript.

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## Appendix A. Supplementary data

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